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LITHIUM-ION CELL TECHNOLOGY DEMONSTRATION FOR FUTURE NASA APPLICATIONS

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ABSTRACT

NASA requires lightweight rechargeable batteries for future missions to Mars and the outer planets that are capable of operating over a wide range of temperatures, with high specific energy and energy densities. Due to their attractive performance characteristics, lithium-ion batteries have been identified as the battery chemistry of choice for a number of future applications, including planetary orbiters, rovers and landers. For example, under the Mars Surveyor Program MSP 01 lithium-ion batteries were developed by Lithion (each being 28 V, 25 Ah, 8-cells, and 9 kg) and fully qualified prior to mission cancellation. In addition to the requirement of being able to supply at least 90 cycles on the surface of Mars, the battery demonstrated operational capability (both charge and discharge) over a large temperature range (–20°C to +40°C), with tolerance to non-operational excursions to –30°C and 50°C.

Currently, JPL is implementing lithium-ion technology on the 2003 Mars Exploration Rover (MER), which will be coupled with a solar array. This mission has similar performance requirements to that of the 2001 Lander in that high energy density and a wide operating temperature range are necessitated. In addition to planetary rover and lander applications, we are also engaged in determining the viability of using lithium-ion technology for orbiter applications that require exceptionally long life (>20,000 cycles at partial depth of discharge). To assess the viability of lithium-ion cells for these applications, a number of performance characterization tests have been performed (at the cell and battery level) on state-of-art prototype lithium- ion cells, including: assessing the cycle life performance (at varying DODs), life characteristics at extreme temperatures (< -10°C and >+40°C), rate capability as a function of temperature (-30° to 40°C), pulse capability, self-discharge and storage characteristics, as well as, mission profile capability. This paper will describe the current and future NASA missions that are considering lithium ion batteries and will contain results of the cell testing conducted to-date to validate the technology for these missions.

INTRODUCTION

NASA has a sustained interest in obtaining batteries that have the potential to further enhance mission capability. Batteries that display higher gravimetric and volumetric energy density, longer cycle life, wider operating temperature range, and better rate capability can all translate into increased spacecraft capability. In many cases, advanced battery technologies can be mission enabling, rather than just enhancing, and may facilitate increased scientific capabilities of the mission, such as with the planetary exploration of Mars.

The first major NASA mission to adopt lithium-ion technology was the 2001 Mars Surveyor Program (MSP01), in which the advanced battery technology was developed for the Mars Lander (this mission was originally scheduled to launch in April 2001, however, it was cancelled by NASA due to programmatic issues). The surface Lander spacecraft for this mission, fabricated by Lockheed-Martin Astronautics in collaboration with JPL, required two Lithium-ion batteries, each being 28 V (eight cells), 25 Ah and 9 kg (18 kg total). (Smart, 1999) In addition to the requirement of being able to supply at least 90 cycles on the surface of Mars after a 1 year storage and cruise time, the battery was expected to be capable of operation (both charge and discharge) over a wide temperature range (–20°C to +40°C), with tolerance to non-operational excursions to –30°C and 50°C. These requirements are much more demanding than those encountered with the previous Mars Pathfinder mission which utilized Ag-Zn technology. (Ratnakumar, 2000) In contrast, the Mars pathfinder battery was only expected to operate between 0 to 30°C and deliver 30 cycles on the surface of Mars. Although the Surveyor mission was cancelled by NASA prior to launch, the Lander battery was fully developed (by Lithion/Yardney Technical Prod.) and flight qualified prior to the program closure (Byers, 2001 and Gitzendanner, 2002). The lithium-ion cell chemistry adopted by Yardney to meet the projected mission requirements consisted of mesocarbon microbeads (MCMB) carbon anodes, $LiNi_xCo_{1-x}O_2$ cathode materials, and a low temperature electrolyte (1.0 M $LiPF_6$ EC+DMC+DEC (1:1:1)) developed at JPL. (Smart, 1997 and 1999)

Given the successful technology-development effort and flight hardware delivery under the Mars Surveyor program, lithium-ion technology has also been selected for incorporation into the 2003 Mars Exploration Rover program currently at JPL. (Ratnakumar, 2002) This mission requires two 24-36 V rechargeable lithium-ion batteries, which are capable of providing ~ 220 WHr of energy during launch, ~160 WHr for supporting any trajectory control maneuvers (TCMs) during cruise, and ~ 280 WHr each Martian day once the rovers have reached the planetary surface. In addition, the batteries must be capable of providing operation for at least 300 cycles on the surface of Mars (~50 % DOD) over a temperature range that varies from –20° to 30°C. In addition, the rechargeable batteries must support multiple 25 A pulses (each 50 mSec in duration) at both ambient and low temperatures.

In addition to these two missions, NASA (JPL and GRC) is considering the use of lithium-ion batteries for a number of other up-coming missions, including the Mars 2009 Smart Lander, future Mars planetary orbiters, and missions targeted at the outer planets ~~(i.e., Saturn's moon Europa)~~. Initial projections for the Mars 2009 Smart Lander necessitated the use of a high energy density battery, which could operate effectively at very low temperatures (down to –40°c) and provide long life (> 3 years of operation on the surface of Mars). This need prompted the Mars Exploration Program to fund a development task at JPL to develop the enabling technology and has lead to improved Li-ion electrolytes that have been demonstrated to provide excellent performance over a wide temperature range (-40 to +40°C). (Smart, 2002) However, recent developments at NASA/JPL which involve the incorporation of radioisotope thermoelectric generators (RTG's), in lieu of solar arrays, have shifted the focus of the battery requirements from enabling a wide temperature range of operation to enabling longer life (> 5 years on the surface of Mars). In addition to future Mars Landers and Rovers, there is interest in using lithium-ion technology for planetary orbiter applications. The high specific energy of lithium-ion technology makes it especially attractive, however, the long life characteristics needed for such applications have not been effectively demonstrated to-date. Thus, in addition to performing very specific mission technology verifications tests (e.g., for the 2001 MSP01 Lander and the 2003 MER Rover), we (at JPL and GRC) are assessing the viability of using lithium-ion technology for a number of future missions, including the ones mentioned. It must be noted that the much of the cell and battery technology (and hardware) development effort was made possible, in part, by the participation of a NASA-Air Force consortium formed in 1998 to establish domestic capability to manufacture lithium-ion cells and batteries in the US. (Marsh, 2001)

GENERAL CELL/BATTERY TEST PLAN

In order to assess the viability of using lithium-ion technology for the present and future NASA applications mentioned, a number of standard performance evaluation tests were implemented on cells received. This enables one to obtain comparative data that is helpful in comparing performance characteristics of cells of varying chemistry, cell size, and cell design. The cell testing procedures generally consist of performing: (a) 100% DOD cycling at different temperatures (-20, 23, and 40°C), (b) variable temperature cycling tests, (c) LEO cycling tests under various conditions (d) discharge and charge rate characterization at different temperatures (-40, -30, -20, 0, 23, and 40°C), (e) storage characterization tests under various conditions, (f) and other mission specific testing. In addition to these standard tests, other characterization tests were performed on selected samples to determine: (i) the effect of charge methodology, (ii) the effect of temperature extremes upon performance, and (iii) the thermal behavior of lithium ion cells. Depending upon the number of samples received in a typical cell lot, the types of tests performed were prioritized and considered with relation to the relevance of up-coming missions.

MSP01 LANDER Li ION BATTERY REQUIREMENTS

The MSP01 mission dictated that a number of performance requirements must be met by the 28 volt, 25.0 Amp-hour batteries to successfully complete the planned mission. Perhaps the most important feature of the battery is its requirement to operate (both charge and discharge) at continuous rate of C/5 over a wide range of temperatures (-20° to +40°C) once the Lander has successfully landed on the surface of Mars. The battery should be capable of providing a minimum EOL capacity of 25 Ah. The typical discharge drains will be C/5 to a maximum of 50% DOD. However, with both the batteries being connected in parallel (with a diode protection), the actual depths of discharge could be even milder than 50%. The maximum charge current is projected to be approximately 5 A (C/5). In addition to operating efficiently on the surface of Mars, the batteries should be able to withstand 50 A pulses at 0°C for short duration, during the entry, descent and landing phase (EDL). In case that the Li-ion batteries are unable to meet this criterion, a thermal battery (Li-FeS_2) was being considered as in the case of Mars Pathfinder, however, recent testing has shown that may not have been necessary. Prior to satisfying both of these requirements, the battery must survive a ground/cruise storage duration of nearly 2 years (6 months to one year pre-cruise storage) and a one year cruise period at 0° to 30°C.

MSP01 LANDER Li ION CELL/BATTERY EVALUATION

In order to assess the viability of using lithium-ion technology for the Mars 2001 Lander, a test plan was formulated by Lockheed-Martin, in collaboration with JPL and Yardney, which reflects the need for data which address the various mission requirements. The test plan generally consists of determining: (i) the room cycle life performance (25°C), (ii) low temperature cycle life performance (-20°C), (iii) discharge and charge rate capability at different temperatures (-20, 0, 25, and 40°C), (iv) pulse capability at different temperatures and different state-of-charge (SOC), (v) optimum storage condition to ensure minimal loss of performance (vi) ability to perform an EDL load profile, and (vii) ability to cycle under surface temperature profile conditions. Although all three institutions performed testing to achieve these ends, the results of the cell testing performed at JPL only will be considered in this paper.

YARDNEY (LITHION) 25 AHr CELL TESTING

CYCLE LIFE PERFORMANCE

According to the projected mission plans, the battery should be capable of providing a minimum of 90 cycles once the spacecraft has reached the surface of Mars. Due to the fluctuating temperatures on the surface of Mars during the course of a typical sol period, the battery will be required to cycle efficiently over wide temperature variations (-20 to +40°C). In addition, successful operation must be demonstrated after being subjected to an extended cruise period (~ 11 months) and an additional storage period from the date of manufacturing and time of launch. In order to assess the viability of the lithium-ion technology to meet these requirements, a combination of tests was undertaken to establish a comprehensive data base to enable predictive performance trends. One general test performed to evaluate the life characteristics involved 100 % DOD cycling of cells between a voltage range of 3.0 Vdc to 4.1 Vdc at a number of temperatures. As illustrated in Fig. 1, 20 Ahr prototype cells have been cycled successfully cycled > 1200 cycles at both ambient temperatures as well as at –20°C (charged and discharged at low temperature).

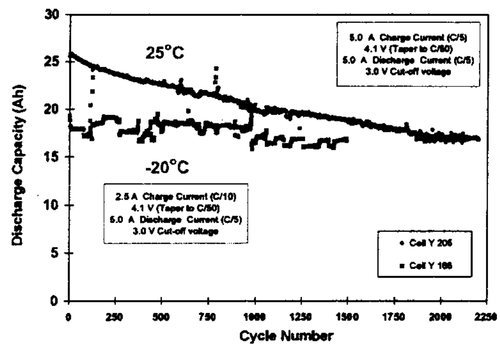

Fig.1. Cycle life performance (100% DOD) of Lithion 20 Ahr prototype lithium-ion cells at 25 and –20°C.

DISCHARGE PERFORMANCE AT DIFFERENT TEMPERATURES

Since demonstration of efficient performance at low temperature was a major technological challenge, a large amount of emphasis was placed upon evaluating the discharge capacity over a number of different rates (C/2, C/3, C/3.3, C/5 and C/10) and temperatures (-30, -20, 0, 23, and 40°C). When Yardney MSP01 design cells were evaluated at a C/5 discharge rate (5.0 Amp discharge to 3.0 V) at different temperatures, good performance was observed over the range of temperatures, as shown in Fig 2. At –20°C, ~ 24 Ahr of capacity was delivered (cell charged at –20°C using a C/10 charge rate to 4.1V), representing ~70% of the room temperature capacity. The cells were also observed to deliver excellent specific energy over a large range of temperatures, with over 85 Wh/kg and 140 Wh/kg being delivered at –20°C and 40°C, respectively

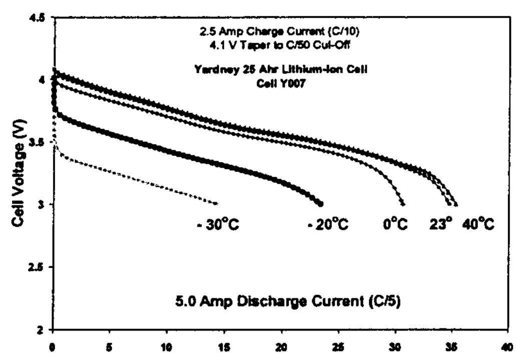

Fig.2. Discharge capacity of a Yardney MSP01 design 25 Ahr cell at a C/5 discharge rate and at different temperatures (-30, -20, 0 , 25 and 40°C).

STORAGE CHARACTERISTICS

In order to assess the capability of the technology to meet the various life requirements, it was necessary to conduct a number of tests to evaluate the effect of prolonged storage upon performance. In the case of the Mars 2001 Lander, the battery must be operational after an 11-month cruise period while the spacecraft is in transit to Mars. The first set of tests were aimed at determining the effect of storage temperature and cell state of charge upon performance when the cells are stored under open circuit conditions (OCV). The cells selected for this testing were of an early generation, 20Ah capacity design. In order to represent the extremes projected for the cruise storage period, two different temperatures were selected (0 and 40°C) and two different states-of-charge (50 and 100%) were utilized. For these initial tests, the cells were: (i) first cycled (5 cycles) prior to storage (ii) stored at the selected temperature and state-of-charge (iii) discharged to 3.0V to determine the residual capacity at 25°C and (iv) then cycled a number of times (5 cycles) to determine the extent of permanent capacity loss of the cells (if any) as a result of the storage period. The cells were first subjected to a two month storage period accompanied by full performance characterization before and after, followed by a longer ten month storage period. In general, minimal permanent capacity loss was observed over the range of conditions investigated, with the largest loss in capacity (~ 11%) with the cells that were stored at high temperature (+40°C). However, if the cells are stored at low temperature (0°C) and low state-of-charge over 96% of the initial capacity is realized after one year of cell storage.

In addition to determining the impact of storage conditions upon the reversible capacity at ambient temperature, the cells were also characterized at low temperature (-20°C). In general, the storage of the cells was observed to affect the low temperature capability more dramatically, and proportionately lower capacities were observed. In contrast to the trend observed when the cells were evaluated at room temperature, the effect of state-of-charge was seen to be more dominant than the effect of temperature upon in determining the low temperature capability. The best results were obtained with a cell which was stored at 50% SOC and at 0°C, with ~66% of the room temperature capacity realized at –20°C (compared to ~ 70 % of the room temperature being delivered prior to the storage characterization tests).

In addition to investigating the effect of storage under OCV conditions, effort has been devoted to evaluating the viability of storing the cells connected to the buss for the duration of the storage period. This is especially relevant due to the fact that the spacecraft design is simplified if the cells are connected to the buss for the duration of the mission. In order to simulate potential cruise conditions, a number of cells (4) were stored for ~11 months connected to the buss and stored at 10°C. The cells were float charged at 3.875 V which corresponds to ~70% SOC. Similar to the methodology described for the previous storage study, all cells were characterized in terms of the reversible capacity before and after storage at various temperatures. Excellent reversible capacity was obtained after 11 months of storage under these conditions, with less that 5% permanent capacity loss observed in all cases.

When the low temperature performance was assessed following the 11 month storage period, less cell to cell variation in performance was observed with cells stored at 10°C and 70% SOC on the buss compared with the group of cells stored under various OCV conditions. The consistency of the values obtained is encouraging when considering potential battery issues related to how well the cells are matching in capacity and performance characteristics throughout the mission life. Only 5-10% reduction in capacity was observed at –20°C after prolonged storage connected to the buss.

Overall, the results indicate that efficient storage of lithium-ion cells can be achieved while connected to the buss if proper conditions are selected. As illustrated in Fig. 3, when the discharge profiles are compared before and after a two-year storage period, very little change in performance is observed, with minimal degradation of operating voltage and minimal capacity loss (< 3%).

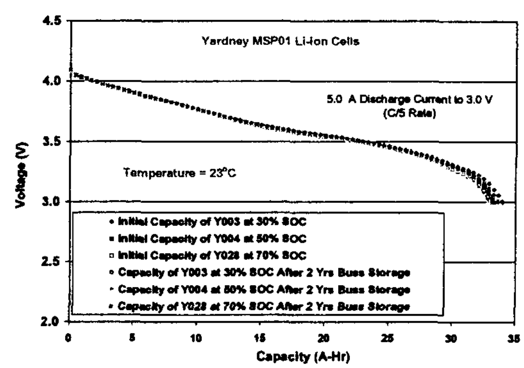

Fig.3. Reversible capacity after two year storage period (cells stored at 0°C at different SOC).

EDL PROFILE

After completing the cruise period, the battery is expected to assist in the entry, descent, and landing process, which involves supplying power to various pyros and landing functions. The most demanding segment of the load profile consists of a 20 Amp discharge current onto which 30 Amp pulses are applied, thus, both contributing to produce 50 Amp loads (2C discharge rate) for short duration (100 milliseconds). In terms of mission requirements, the ability to sustain cell voltages above 3.0 V throughout the duration of this test at 0°C is the most difficult to fulfill.

Since performance data relating to the EDL load profile is more relevant on cells which have been subjected to prolonged storage to simulate the cruise phase of the mission, the tests were performed on the group of cells previously described which were stored under OCV conditions. Due to the variation in cell performance observed after the differing storage conditions, some variation in cell polarization was expected when subjected to the high current loads. This indeed was the case, with the cells which were subjected to conditions of high state of charge displaying the greatest cell polarization and the inability to sustain a voltage greater that 3.0 V during the high current (50 Amp) pulses. In contrast, the cells stored at low state-of-charge were able to maintain much higher operating voltages throughout the duration of the load profile, never dipping lower than 3.2 V. Again it should be noted that these cells were of an earlier generation, 20Ah capacity design and thus not designed to meet these pulse requirements

Similar to the trends discussed earlier in relation to the low temperature capabilities, the state-of-charge during storage appears to have more influence upon the pulse capability compared to temperature of storage.

In addition to the group of cells that were stored under OCV conditions, the MSP01 design cells that were stored on the buss for 11 months were also subjected to the EDL profile. As shown in Fig. 4, excellent results were obtained being capable of successfully meeting the mission objectives, with the operating voltages never dipping below 3.4 V throughout the load profile.

In addition, very consistent data was obtained for the four cells studied, which were stored under identical conditions (10°C, 70% SOC = 3.875 V) prior to the pulsing test.

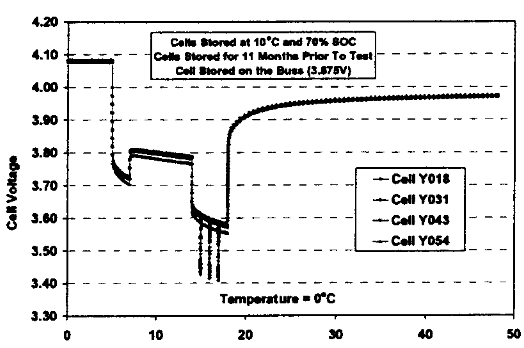

Fig. 4. EDL profile of Yardney MSP01 25 Ahr cells after being subjected to11 months storage connected to the buss.

MISSION SURFACE OPERATION SIMULATION

Once the spacecraft has landed on the surface of Mars, the battery is expected to cycle successfully for a minimum of 90 sols, with the desire of successfully completing at least 200 cycles. According to the current estimates of the Martian surface temperature profile, and the corresponding temperature swings that will be experienced within the Lander thermal enclosure, the battery will be expected to operate over a large range of temperatures (Δ 60°C). In order to simulate the battery operation over the course of the entire mission, a number of temperature ranges were investigated which correlate to the projected battery environment as the Martian season begins to change. These ranges are characterized by the widest temperature swings experienced in the beginning of the mission, and less severe, but colder temperature ranges later in the mission. Thus, continuous cycling was performed under the following conditions: (a) 20 cycles (days) over a temperature range of –20°C to 40°C, (b) 10 cycles at –20°C to 30°C, (c) 10 cycles at –20°C to 20°C, and a (d) 100 cycles at –20°C to 10°C. The electrical profile during this cycling consists of charging the cells with a constant current (C/5 rate) to 4.1V for a total charge time of 12 hrs, and a relatively mild discharge current (1 Amp or C/25 rate) for a total of 12 hrs, corresponding to 12 Ahr of capacity (~40% DOD). For a typical mission simulation cycle, the beginning of the charge period occurs when the battery experiences the coldest temperatures, whereas, the beginning of the discharge period commences when the highest temperatures are experienced.

Due to the fact that a fixed amount of capacity is discharged each cycle (12 Ahr), the performance characteristics of the mission simulation cycling is most adequately expressed in terms of the end-of-discharge voltage. The end of life for the cells subjected to this test has been designated as being when the cells drop below 3.0 V upon discharge. As illustrated in Fig. 5, when prototype 20 Ahr cells were cycled under these conditions, successful completion of over 550 cycles has been observed over a number of different temperature ranges as previously described. These cells had previously been subjected to a 12-month OCV storage and EDL pulsing (described earlier) prior to the mission simulation testing. Thus, the observed cell performance is especially relevant, since the cell histories prior to the mission simulation profile testing reflect similar conditions to that expected to be experienced by the actual Lander battery. The fact that the operating cell voltages never dip below 3.4 V, and display little capacity fade, is encouraging in terms of meeting the mission requirement previously described. Even more relevant mission simulation testing data is currently being generated on the MSP01 design cells which were previously stored on the buss at 10°C (70% SOC), which more adequately represents the actual projected storage conditions.

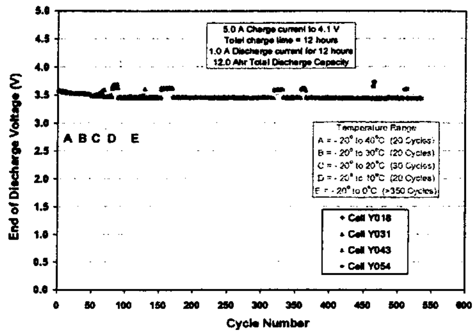

Fig.5. Mission simulation cycling of Yardney prototype MSP01 lithium-ion cells.

MSP01 8-Cell Battery Testing Results

Prior to the discontinuation of the mission, Yardney delivered a number of flight batteries to the project consisting of 8-cell, 25 AHr (nameplate capacity) modules. During the course of the program, Yardney successfully space-qualified the battery design which was observed to meet all specified requirements, including shock and vibe, thermal vacuum, capacity, and abuse requirements. As shown in Fig. 6, when the battery was charged to 32.8V (tested without charge control methodology developed at LMA) and discharged to 24V over 32 AHr was delivered, corresponding to 932 WHr or ~ 105 WHr/kg. Good cell dispersion characteristics were generally observed given periodic cell balancing (cells resistively discharged) suggesting minimal reliance upon charge control methodologies implemented. When the battery was evaluated at –20°C, similar trends were obtained to that observed at the cell level with ~ 75% of the room temperature capacity being delivered.

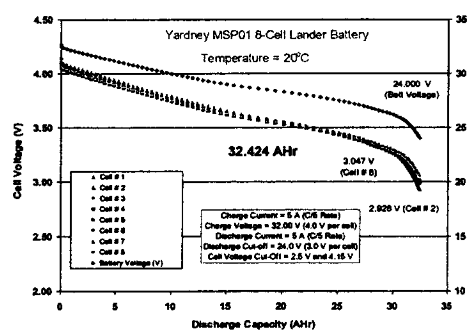

Fig. 6. Discharge capacity of the MSP01 8-cell Lander battery at 20°C (32.8V charge).

After initial characterization, the 8-cell Lander battery was subjected to a 11-month storage period under constant applied voltage (corresponding to ~ 70% SOC) at a temperature of 10°C. As shown in Fig. 8, increased cell dispersion was observed as a result of the storage period and necessitated cell balancing protocols (e.g., resistively discharging each cell to 2.5V) to obtain full capacity. After cell balancing, the battery was observed to deliver >95% of the initial capacity displaying very similar trends to that obtained at the cell level. After completing the post-storage characterization of the battery, we intend to implement a surface operation mission simulation test similar to that described previously.

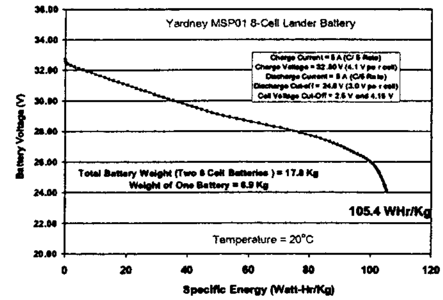

Fig.7. Specific energy of the MSP01 8-cell Lander battery at 20°C (32.8V charge).

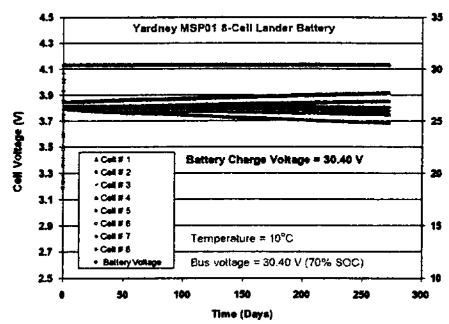

Fig.8. Cruise simulation testing of the MSP01 8-cell Lander battery at 10°C (~ 70 SOC).

2003 MER ROVER Li ION CELL/BATTERY REQUIREMENTS AND TEST PLAN

Although many of the performance requirements of the MER program are similar to that the MSP01 Lander, significant differences are present including: 1) different cell size (8 AHr vs. 25 AHr), 2) more aggressive EDL load profile, 3) more demanding launch and cruise support, and 4) higher discharge and charge rate requirements during surface operation. In general, The function of the MER batteries is to; 1) provide power during launch procedures, 2) provide power during cruise (attitude adjustment), 3) support the pyro events during the entry-descent, and landing of the spacecraft, and 4) provide power to the rover vehicle on Mars for at least 90 sols (day/night cycle). Given the parallel development of a previously unavailable cell size at Yardney (10 AHr), many of the characterization tests performed at JPL were on 7 Ahr prismatic cells of similar design obtained under earlier programs (1-2 years old prior to testing). In addition to addressing the unique mission requirements of MER, generic characterization tests were also performed to assess the overall performance.

CYCLE LIFE PERFORMANCE OF 2003 MER PROTOTYPE CELLS (YARDNEY 7 AHR CELLS)

To assess the cycle life performance of the prototype cells, 100% DOD cycling was performed at different temperatures (40, 23, and –20°C). In general, very comparable results were obtained compared to previously evaluated prototypes and exceeded mission requirements (only 300 cycles). To address project concerns, cells were also cycled in an inverted position (upside-down) to determine if there are any deleterious effects. As shown in Fig. 9, when cells were cycled in the inverted position (at 40°C to accelerate any potential problems) no ill effect was observed (i.e, increased capacity fade or catastrophic failure).

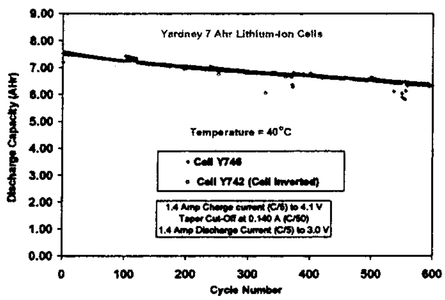

Fig. 9. Assessment of the impact of cycling cells in an inverted position (100% DOD at 40°C).

EDL TESTING OF 2003 MER CELLS

As mentioned previously, the MER mission requires that the battery support a number of pyro events during the entry-descent-landing period. More specifically, the cells should be capable of supporting 42 pulses (25 A each of 50 mSec duration) at 0°C. As shown in Fig. 10, when 7 AHr cells were subjected to a series of pulses (pro-rated for the smaller cell size) at different state-of-charge, good performance was obtained even at –10°C

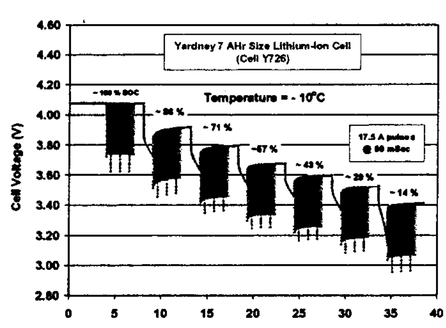

Fig.10. Pulse capability of a 7 AHr Yardney cell at - 10°C at different SOC (21 A pulses of 50mSec duration).

In addition to determining the pulse characteristics of the cells, surface operation mission simulation tests were also performed. As mentioned previously, although the depth-of-discharge is similar, the charge and discharge rates of the mission load profile are more demanding than that observed with the MSP01 Lander (~ C/5 rates) and generally involves colder temperatures initially (approximately 0° to –20°C), as shown in Fig. 11.

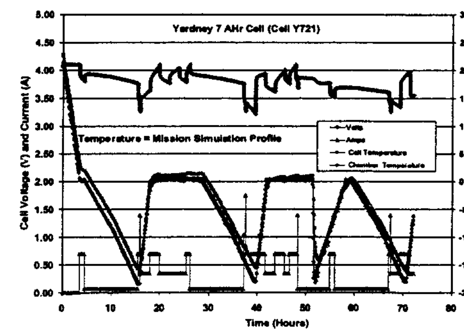

Fig.11. Mission simulation cycling of Yardney 7 AHr prototype MER lithium-ion cells.

In the course of the performance evaluation, a number of temperature ranges and increased load profiles were assessed (to simulate different thermal conditions and the response if one battery fails). Continuous operation was demonstrated over 15 sols with limited loss of performance (represents conditions without charge control).

PERFORMANCE TESTING OF 2003 MER RBAU

In response to the project needs, Yardney/JPL has developed a Li-Ion Rover Battery Assembly Unit (RBAU) which is comprised of two separately wired 8 AHr batteries (nameplate capacity). As shown in Fig. 12, the MER 8-cell batteries delivered > 10 AHr at 20°C and > 75% of the room temperature capacity at –20°C. This trend is very comparable to that observed with the MSP01 Lander cells and the 7 AHr cells previously evaluated of similar chemistry.

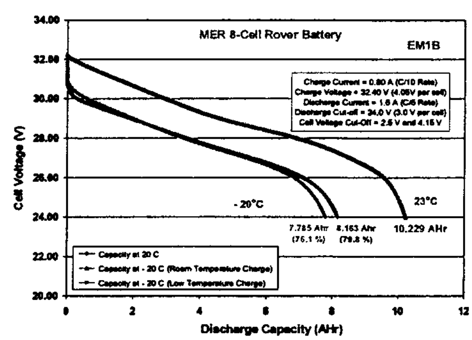

Fig.12. Discharge capacity of the MER 8-cell Rover battery at 20° and –20°C (C/5 rate).

In addition to characterizing the charge and discharge capacity of the RBAU as a function of temperature and charge voltage, mission specific testing was performed in a similar manner to that described at the cell level. In general, better results were obtained at the battery level in contrast to the results observed with the 7 AHr cells. This is believed to be due to the fact that the cells are newer and the thermal effects at the battery level help to heat the cells at low temperatures. For example, when the surface operation mission simulation testing was performed on the MER battery, as shown in Fig. 13, higher cell voltages were obtained in all cases when compared to the data obtained on the 7 AHr cells (the load profile was scaled according to the respective cell sizes). To date, over 12 sols (out of a mission requirement of 90 sols) have been demonstrated at the battery level without the benefit of charge control (charge and discharge defined by battery voltage while using high and low cell voltages limits), suggesting that the battery can meet the mission specifications.

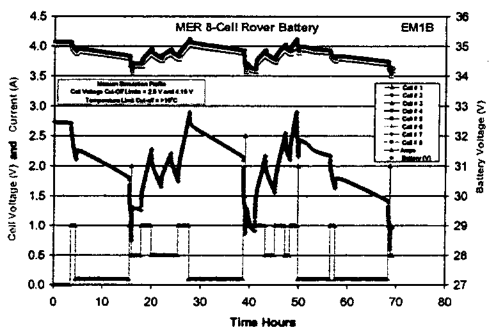

Fig.13. Surface operation mission simulation testing of a MER 8-cell Rover battery.

Conclusions

Lithium–ion cells and batteries have been subjected to a number of performance evaluation tests to determine their viability to satisfy the requirements of past, present, and future missions. Yardney MSP01 Lander cells have been demonstrated to exhibit a) high capacity over a wide range of temperatures, b) excellent cycle life characteristics, c) good storage characteristics with minimal irreversible capacity loss, and d) good pulse capability. In addition, the cells/batteries have met and/or exceeded all of the MSP01 mission requirements and was fully space qualified prior to mission cancellation by NASA. In response to the mission needs of the 2003 MER project, 10 AHr (nameplate capacity of 8 AHr) and 7 AHr cells and batteries have been developed by Yardney consisting of a similar chemistry to that of the MSP01 program. A number of performance evaluation tests have also been performed on these cells and batteries and have been shown to display very comparable behavior to the MSP01 design cells/batteries. The cells/batteries have also been shown to meet the unique, and in some cases, demanding performance requirements of the MER project, including: a) good performance in inverted orientations, b) good pulse capability over a range of temperatures and SOC, c) and the ability to operate continuously at low temperatures (i.e., -20 to 0°C) using moderate rate to simulate operation on the surface of Mars. To ensure optimal cell/battery health once the spacecraft has reached Mars, it is recommended that the battery be maintained at a low state-of-charge (< 70%) and at low temperature (< 10°C) during cruise.

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